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Methods to assess renovation impact on indoor hygrothermal quality in a historical art gallery

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Abstract

This paper presents a set of methods for renovation impact assessment of indoor hygrothermal conditions in a culturally significant historical building functioning as art gallery. The methods used a new synthetic parameter, Renovation Impact Index (RII), which is developed in this study. The RII is defined as performance gradient of the indoor hygrothermal conditions over two annual periods – a year before renovation and the same afterwards. This performance used in defining RII was captured by adopting the Performance Index (PI) concept, used in recent studies. The performances of the two most critical parameters to artwork conservation – indoor air Temperature (T) and Relative Humidity (RH) were assessed with respect to artwork conservation requirements. In this study, PI was defined over two spectra – tight environmental set-points specified in BS5454 Standard for collections care, and a relaxed seasonal set-point strategy owing to its energy saving potentials. Global PI was obtained as a combined effect of T and RH on the overall hygrothermal performance relative to the desired specifications. Seasonal analysis was undertaken for detailed study of renovation impact on individual seasons. Results revealed the positive effects of the renovation solutions with the indoor environment now being less influenced by outdoor weather changes. In addition to energy saving of 27%, the positive overall RII estimate indicated improvement in hygrothermal performance and further quantified it. Seasonal RII indicated that summer experiences poor indoor T conditions relative to BS5454 standards even after refurbishment. Winter experienced the most significant hygrothermal improvements especially with RH. While the gallery space experienced a very stable hygrothermal environment, Fluctuation RII highlighted the only scope for improvement being in the case

of hourly RH fluctuations. The proposed methods can be extended to other renovation projects in similar buildings for impact study and assisting the building management on targeting adequate future improvements.

Keywords

Renovation impact, Hygrothermal performance, Performance Index, Artwork conservation, Historical buildings, Indoor environment, Assessment methods

Abbreviations

AHU Air Handling Unit
NGS National Galleries of Scotland, Edinburgh, UK
BS British Standard (Technical Guidance Document for Historical Collections Care)
HVAC Heating Ventilation and Air Conditioning

Nomenclature

| | |
|----------------------------------|--|
| T | Dry bulb Air Temperature (°C) |
| RH | Relative Humidity (%) |
| PI | Performance Index (%) |
| RII | Renovation Impact Index (%) |
| $\Delta T_{1H}/\Delta RH_{1H}$ | Hourly Temperature/Humidity Fluctuation (°C/%) |
| $\Delta T_{24H}/\Delta RH_{24H}$ | Daily Temperature/Humidity Fluctuation (°C/%) |
| T_n/RH_n | Temperature/Humidity at n^{th} hour (°C/%) |
| T_{n+1}/RH_{n+1} | Temperature/Humidity at $n+1^{th}$ hour (°C/%) |
| $T_{d,max}/RH_{d,max}$ | Maximum daily Temperature/Humidity (°C/%) |
| $T_{d,min}/RH_{d,min}$ | Minimum daily Temperature/Humidity (°C/%) |

1. Introduction

Historical buildings give a character to a region and bring a sense of identity, pride and belonging, for the local public. Some of them function as an art gallery, displaying artefacts mirroring our rich cultural heritage, the unique and irreplaceable witness of our past. In the recent years, there has been a growing interest on the topic of optimised microclimatic control for the preservation of these historical collections [1–6]. These artworks are usually displayed, in open, to visitors and in due course of time, any changes to these delicate historical collections are irreversible and can inflict severe damage upon them [5,7,8]. The two most important parameters responsible for the degradation of artworks are found to be air temperature (T) [8–10] and relative humidity (RH) [11–13].

Technical documents, such as standards for collections care, specify the optimum indoor environment for preservation of the housed collections. These documents also manifest the tight nature of indoor T/RH control. This demands continuous indoor environmental monitoring and control which in turn seeks more investment of Heating Ventilation and Air Conditioning (HVAC) energy demand [4,14,15].

The management of these special function buildings seek to various renovation measures to provide adequate indoor environment while ensuring optimised energy usage. However, when dealing with historical buildings, intervention measures are constrained by architectural preservation requirements. Even the environmental monitoring techniques are strictly limited to the ones being non-invasive and non-destructive, which poses a serious scientific and methodological restriction problem [2,16,17].

The National Galleries of Scotland (NGS), a mid-19th Century Scottish heritage building in Edinburgh, have recently introduced some renovation measures in its attempt to deliver an improved indoor environment - hygrothermal condition for the preservation of its rich and diverse artwork collection along with energy saving. Some of the problems identified include – inadequate room T and RH with a constant trend of their diurnal fluctuations, unbalanced air change rates between the gallery rooms, and significant amount of heat loss through the single-glazed skylights. Now that the renovation features are implemented, there is a need for a comprehensive review of the indoor hygrothermal condition and study the impact of the renovation.

There is a rich literature on assessment methods for indoor environment in such special purpose buildings; while some works are focused entirely on the two hygrothermal parameters – T and RH [5,17–19], others investigated on a combination of the effects of the same along with pollutants, lighting and heat gains [1,20]. However, there is a lack of assessment methods to study the direct impact of renovation measures on the indoor environment after their respective implementation; with existing literature focusing entirely on the projection of improvements by implementing various renovation measures in the form of case studies, numerical modelling and simulations [21–25]. Only after understanding the real-world impacts of the current renovation measures, the building management can target and plan adequate future improvements through effective renovation works. In addition, similar institutional buildings can take a cue from such renovation impact assessments and project the corresponding benefits once they adopt the same renovation measures in their building.

Targeting this gap in existing literature, this paper adopted some existing methods to assess the indoor microclimatic performance [5,18,19] and applied them in the restrictive art gallery environment at the NGS. The adopted methods provided input to a new synthetic index developed in this study. This index, termed as *Renovation Impact Index* (RII) estimated the extent of effectiveness of the refurbishment activities towards fulfilling the desired goals, which in this case was ensuring an optimum indoor environment for the good health of the housed collections. The RRI calculations were based on an established concept, Performance Index (PI)

[5,7,18], which captures the performance of the indoor hygrothermal conditions relative to the conservation requirements.

The NGS building environment is described in [Section 2](#), followed by a detailed description of the refurbishment regime in [Section 3](#). The monitoring campaign and the data sources are enlisted in [Section 4](#). The methodologies developed for the indoor hygrothermal analysis and renovation impact study is described in [Section 5](#). The results achieved are presented and discussed in [Section 6](#), while [Section 7](#) draws the conclusions from this.

2. The National Galleries of Scotland (NGS)

Built in the mid-19th century, this neoclassical building houses a number of important and highly valuable European masterpieces and Scottish works; the collection of Fine Arts regarded as amongst the best in the world, currently with over 96,000 works in the permanent collection. The art collection ranges from the period of 14th Century Gothic Renaissance up to the early 20th Century Scottish Art. Apart from the famous artworks, the building itself is classified by the Scottish Government as an ‘A listed’ building. This highlights its international importance and the restrictions imposed to protect the character of the building (special architectural or historic interest) whilst allowing its continued use.

The building is stone-built with thick exterior walls of over one metre in width. The walls also are without fenestration and all the natural light in the building comes from the skylights installed at the curved roof cupolas [21]. The extensive use of sandstones for the external wall along with the brick-walled internal partitions significantly contributes towards the high thermal mass of the building. The paintings are mostly of the type ‘oil on canvas’ or ‘oil on panel’. Apart from the paintings, collections also comprised of work on paper, photographs, sculptures made of wood, plaster and metal.

Figure 1: NGS – Outside view (left), NGS Floor Plan with Gallery 11 highlighted (right)

In order to ensure the good health of these delicate historical collections, it is a must to have a tight indoor microclimatic control. The optimum environmental specifications are defined in various technical documents, known as *Standards for Collection Care*. Different Standards are followed in different parts of the world. In the UK, the British Standards 5454 – ‘*Guide for the storage and exhibition of archival documents*’ is primarily followed. This official document provides the specifications for adequate indoor hygrothermal conditions, lighting, and practices for ensuring good health of the housed collections. The NGS mainly follows the BS 5454 Standards in addition to slight modifications based on the nature, type and origin of certain special international

exhibits loaned to the Galleries. Table 1 summarises the key thresholds for the two indoor hygrothermal parameters critical for artwork conservation – T and RH, along with the threshold for their temporal fluctuations.

Table 1: Standards for Collection Care followed at NGS

The tight indoor microclimatic condition required in the NGS is provided by a set of dedicated Air Handling Units (AHU). Each air handling unit provides a mixture of fresh air and recirculated air, filtration, heating, cooling, humidification and dehumidification via insulated ductwork at roof level. The treated air enters the gallery spaces through linear grilles located at high level and return air at low level. Air flow to each gallery space is fixed by manual dampers in the duct and the fans operate at constant speed. The plant is controlled by the Building Management System (BMS) with its current control philosophy set to achieve the desired indoor environmental conditions as specified in Table 1.

3. Refurbishment

The NGS, similar to other museums and art galleries around the world, have been wrestling with the problem of striking the balance between reducing the high energy consumption on one hand, and traditional conservation requirements of tightly controlled indoor T and RH on the other hand. Furthermore, it was observed that the existing roof structures were uninsulated, with visible gaps along the perimeter of the skylights. This threatens to influence the interior space of the galleries with the external diurnal T and RH fluctuations which can be detrimental for the health of the housed collections. The skylights were single glazed, hence contributing to poor thermal inertia. The weakness of skylights was further confirmed by a number of observed condensation forming over the inner surfaces of the skylight glazing, owing to the low surface temperature of the glass used.

Commissioned by the NGS, a review of the existing environmental conditions inside the Galleries was undertaken in order to identify the deficiencies and to provide recommendations to improve these conditions within various rooms and also reduce the energy consumption. Based on some of the key findings and recommendations, the NGS undertook a set of refurbishment activities as detailed in Table 2. The review highlighted that the Gallery rooms catered by AHU-1 were associated with the maximum problems, such as the poor air change rates, and a perceived colder feeling compared to the other rooms.

Table 2: Refurbishment activity at the NGS

The expectation from skylight upgrade was to improve the high fabric heat loss problem leading to reduced heating demand in the colder seasons. The fabric insulation would ensure that the building is less affected by outdoor

weather changes, otherwise in addition to increased heat demand during cold weather there will remain this source of unwanted fluctuations in indoor T and RH. The reconfigured supply ducting of the AHUs would enable uniform supply air flow to all the gallery rooms. The increased fan speeds would improve the supply air flow rate to adequate levels, which will efficiently meet the demands for a sound performing indoor hygrothermal environment in its pursuit to maintain the conservation requirements. However, there was no post-renovation impact assessment of the building to study whether the expected changes actually existed in real, which led to this study.

4. Monitoring Campaign

To understand the microclimatic behaviour and study the effects of the refurbishment regime, an extensive indoor environmental monitoring was conducted inside the NGS. The monitoring system was installed in one particular room – Gallery 11 (Figure 2), owing to the ease of access for installations, management permission, archive data availability and the fact that it represents most of the other gallery rooms, in terms of shape and function. Moreover, Gallery 11 is served by AHU – 1, which was reviewed to be the unit with the maximum associated indoor environmental problems. Gallery 11 is also an important recipient of the refurbishment activity, with the upgradation of skylight and the balancing of AHU1.

Figure 2: NGS Gallery 11 interior (left), Cross Section of Gallery 11 (right)

The monitoring campaign started on May 2012 and is still in progress. In this paper, a comparative analysis is performed from the data pertaining to two annual periods – before and after the renovation, to study its effects.

The data sources consisted of a combination of BMS sensors and additional installed sensors. Targeting the two critical hygrothermal parameters for artwork conservation, the BMS sensors considered for the study pertained to Gallery 11 room dry-bulb Temperature (°C) and room Relative Humidity (%RH), recorded at every 15 minute intervals. These records are stored at the BMS central server and are available upon request from the management team. Additional sensors (Table 3) were installed at different heights in Gallery 11 to observe the room T/RH in different locations. The various heights, as shown in Figure 2, chosen for installation are – visitor level (1.5m), 1st Floor level (6.5m), Ceiling level (8.5m) and Skylight surface level (9m). As the space was an operational gallery, only limited sensors were eligible for installation owing to building management restrictions.

Table 3 – Tiny Tag Ultra2 Temperature/Humidity Loggers (TGU-4500)

5. Assessment Methodology

In order to study the overall effectiveness of the refurbishment plan at the NGS towards meeting the goals of improved indoor environment for artwork conservation, it is imperative to first obtain a mean to quantify the ‘performance’ of the indoor environment with respect to the conservation requirements for the two hygrothermal parameters critical for artwork conservation – T and RH. Recent studies [5,7,18] discusses about using a certain synthetic index, called Performance Index (PI), to measure the indoor environmental quality relative to the desired conditions. This study adopted the concept and defined the PI for a hygrothermal parameter, as a percentage of the number of cases, out of the total cases in the period of study, in which the parameter existed within the optimal range specified in standards. The NGS follows The BS5454 Standard, which defines the optimum ranges for indoor T and RH.

$$PI_p(\%) = \frac{n(p)_{\alpha < p < \beta}}{n(p)} \times 100 \quad (1)$$

Where, PI_p is the percentage score of the level of adherence of the parameter p , towards the optimal range limited between the upper and lower thresholds, α and β , respectively.

PI quantifications were calculated for two annual periods in order to make the comparisons – an annual temporal profile ‘before’ the refurbishment, and an annual temporal profile ‘after’ the refurbishment, for each parameter. The study then developed a new synthetic index, Renovation Impact Index (RII), to quantify and assess the renovation impacts. The RII for a parameter was defined as a gradient of the indoor performance of the parameter, in terms of PI, before and after the refurbishment. Hence, the RII acted as a tool to directly understand the impact of a renovation measure on a particular hygrothermal parameter in terms of its performance change around the intervention period.

$$RII_p(\%) = \Delta PI_p = \left[\left(\frac{n(p)_{\alpha < p < \beta}}{n(p)} \right)_{after} - \left(\frac{n(p)_{\alpha < p < \beta}}{n(p)} \right)_{before} \right] \times 100 \quad (2)$$

Where, $RII_p(\%)$ is the Renovation Impact Index of a parameter, p , and ΔPI_p is the change in the performance index estimate of the parameter after the refurbishment relative to the performance index before.

To study the combined performance and correlation of the two indoor hygrothermal parameters, the Global PI concept [7,18] was adopted. In this concept, a correlation of indoor T and RH is obtained which form a cluster of data-points representing the overall hygrothermal performance. This performance can then be checked with respect to a window defined by the desired specifications for T and RH. The data points inside the fixed window will represent the number of times in which both the parameters exist within the specifications over an annual period. Since the NGS follows this standard, in this study, the BS5454 specifications was used to define this fixed window, and furthermore defining the PI for T and RH. Global RII was then estimated using the Global PI gradient at annual periods across the intervention event to study the renovation impact over a year.

In order to study the seasonal influence on the renovation effects, the annual temporal profiles were further zoomed in on a seasonal scale by splitting the year into three seasons – cold, hot and mild. The study assessed the renovation affects in a different spectra defined by a varying optimum control range for indoor T and RH in the three seasons. These adaptable seasonal bands were chosen using a combination of ASHRAE specifications [26], and suggestions made to the Galleries by their contractor, Harley Haddow Consultants, after their assessment of the building performance. The study then integrated the Global PI concept with the seasonal perspective analysis by using these variable seasonal bands, termed as ‘safe zones’. Table 4 highlights the thresholds for T and RH in the three seasons. Seasonal Global RII was then estimated as the change in Global PI estimates after the refurbishment relative to the estimates before, for individual seasons in order to study the intervention impact in individual seasons.

Table 4 – Seasonal safe band specifications for the hygrothermal variables

To study the seasonal influence on intervention impact for each individual parameter – T and RH, a representative month from each of the three seasons was chosen, based on the worst case scenarios. For instance, the coldest and hottest months were chosen in the winter and summer periods, respectively. The mild month was chosen with temperature values existing as a mid-point of the hot and cold cases, along with having the most varying outdoor humidity throughout the month. Both the windows – fixed and relaxed, were used to understand how the indoor environment performed relative to the different specifications. Seasonal RII was calculated from the gradient of the Seasonal PI figures across the refurbishment event, indicating the improvement estimate for each specification window separately.

The study assessed the renovation effects on the stability of the indoor hygrothermal conditions by defining temporal fluctuation parameters aligning with the ones defined in [7,18], for indoor T and RH. The parameters in this study were defined in a way so as to match the desired thresholds for optimum indoor hygrothermal stability for collections care followed by the NGS, as listed in Table 2. In this study the hourly fluctuation parameters for indoor T and RH were defined as –

$$\Delta T_{1H} = T_n - T_{n+1} \quad (3)$$

$$\Delta RH_{1H} = RH_n - RH_{n+1} \quad (4)$$

Where, ΔT_{1H} and ΔRH_{1H} are the hourly T and RH fluctuation parameters; $T_n(^{\circ}\text{C})$, $RH_n(\%RH)$ corresponds to T and RH at the n^{th} hour, and $T_{n+1}(^{\circ}\text{C})$ and $RH_{n+1}(\%RH)$ are the corresponding T and RH values at $(n+1)^{th}$ hour, respectively.

And, the daily fluctuation parameters for indoor T and RH in this study were defined as –

$$\Delta T_{24H} = T_{dmax} - T_{dmin} \quad (5)$$

$$\Delta RH_{24H} = RH_{dmax} - RH_{dmin} \quad (6)$$

Where, ΔT_{24H} and ΔRH_{24H} are the daily temperature and RH fluctuation parameters, $T_{dmax}(^{\circ}\text{C})$, $T_{dmin}(^{\circ}\text{C})$, $RH_{dmax}(\%RH)$, and $RH_{dmin}(\%RH)$ are the corresponding maximum and minimum values of daily outdoor T and RH, respectively.

Fluctuation RII was estimated as a gradient of the PI for the each of the four fluctuation parameters, across the refurbishment event.

6. Results and Discussions

In theory, the four renovation activities undertaken by the NGS should collectively yield an improved indoor environment for collections care along with reducing the building's energy usage associated with the air handling system. This study reveals the extent of the improvement by quantifying the impacts of the renovation interventions on the indoor hygrothermal environment.

The NGS AHUs rely on gas for heating applications and electricity for cooling and dehumidification. After calculating the annual gas and electricity consumption for the total treated floor area, it can be observed that while

electricity consumption improved by 17%, gas consumption improved even more by 27%, after refurbishment (Table 5). This reduced heating energy use owes primarily to the combination of skylight upgrade and building fabric insulation. While the double glazed skylights have lowered the building's fabric heat loss, the fabric insulation enables the building to better resist the influence of external weather changes. Hence, the building now increasingly retains indoor heat than before, which is an attribute important to have in the cold Edinburgh climate.

Table 5 - NGS energy use comparisons and RII for annual temporal profile of indoor T/RH

Figure 3 - Comparison of Annual Indoor Environmental Control Quality (Before and After Refurbishment)

As for the indoor hygrothermal performance, it can be seen that the parameters existed more within the tight BS5454 specifications after renovation (Figure 3). Before, the gallery space remained dangerously dry (less than 30% RH) for durations of as long as over a month. A positive RII owing to the improved PIs, after renovation, for both T and RH further highlighted the renovation success (Table 5).

Table 6 – Global RII comparison for annual temporal profile of indoor T/RH and individual seasonal performances (PI)

Figure 4 – Annual comparison of Global PI for T against RH, before and after the refurbishment (with Fixed Band Window)

To analyse the effects of renovation on both T and RH combined, Global PI concept [7,18] was implemented in which T was plotted against RH for an annual period and compared for the period before and after refurbishment (Figure 4). On checking the hygrothermal performance through the 'tight' window representing the BS5454 T and RH specifications, it was clear that the indoor environment continued to remain hot and dry beyond the specifications with 11% cases, which existed in the 'fixed' window, improved to about 27% after refurbishment (Table 6). This results from overheating of the cold outdoor air which enters the room and becomes dry, demanding adequate humidification. The hygrothermal performance is much better if looked through the 'relaxed' window, with 97% cases existing within the 'relaxed' T and RH specifications. RII demonstrates that the improvement is more pronounced in the case of the fixed window. This improvement is a direct result of the improved supply air flow rate achieved by increased fan speed and balancing the AHUs with reconfigured supply ducts from AHU to the various rooms. As the air flow rate in Gallery 11 is now desirably higher than it was before, the supply T and RH efficiently offsets the changes incurred by the variations brought by occupants and external

weather. This also enables all the gallery rooms, which are of similar volume and building type, to be uniformly served by the AHU supply of T and RH.

Figure 5 – Seasonal comparison of Global PI for T against RH, before (Top) and after (Bottom) refurbishment (with Adaptable Seasonal Windows)

Figure 6– Global RII comparison for improvements in two spectra – Fixed BS5454 set-points and Adaptable Seasonal Set-points strategy

A closer look at the hygrothermal performance in each individual seasons (Figure 5) reveal a certain improvement after the intervention measures, in individual seasons, with Seasonal RII describing the extent of this improvement (Table 6). The winter and mild months are the recipient of maximum improvement (Figure 6). Winter month when looked through the ‘fixed’ window improved significantly from a very poor indoor hygrothermal performance of 10% to 70% on Global PI scale. This is a direct result of improved building fabric insulation, which ensured less infiltration of the cold winter air from outside before it gets heated to thermal comfort but not adequately humidified. However, to explain the cause for this improvement, T and RH were studied separately (Figure 7) and checked against the BS5454 specifications. A clear pattern can be noticed in the three seasons - the indoor RH would exist below the lower threshold of the BS5454 set-points and T would remain at the higher side, especially in mild and summer months. This further indicates over-heating of the air supplied to room. In addition to improved fabric insulation, the upgraded skylight ensured the interior space retains more heat leading to reduced requirement for heating, which then obviously eliminates any chance of over-heating.

Figure 7 - Seasonal analysis - Indoor environment in a) Cold month b) Mild month c) Hot month

Figure 8 – Seasonal RII for indoor T and RH over two spectra – Fixed BS5454 set-points and Adaptable Seasonal Set-points strategy

Table 7: Seasonal influence on RII on two spectra – a) Fixed BS5454 standards b) Adaptive Seasonal bands

Figure 7 also reveals that while RH performance improves, especially during the mild and hot months, T experiences a poor performance even after refurbishment. Table 7 further highlights that the only negative RII figures in this study are obtained for indoor T during summer months indicating performance deterioration after renovation. However, this becomes less concerning if we check in the same table that the performance of T after refurbishment is 90% (PI) if looked through the seasonal set-point window. This can be further justified by the fact that main concern during the hot months is RH, which is more critical for artwork conservation than T. Hence,

T is deliberately allowed to drift more loosely in order to maintain an adequate indoor RH. Figure 8 further supports this observation by revealing that the RH performance has improved the most if looked through both the fixed BS5454 and adaptable seasonal windows.

Figure 9 - Comparison of T and RH fluctuations before and after the refurbishment for a year – a) daily fluctuations b) hourly fluctuations

Table 8: RII for indoor hygrothermal stability – hourly and daily fluctuations

The NGS experiences a very good performance in terms of indoor hygrothermal stability in the cases of both daily and hourly fluctuations (Figure 9). It can be seen that only hourly RH had the scope for improvement, which it did after the refurbishment and the Fluctuation RII (Table 8) provides the extent of this improvement. While the skylight upgrade and building fabric insulation has made the building more robust to external weather changes, improved and adequate supply air flow rates further maintains the desired stability. It is also worth noting that the high thermal mass of the building fabric helps to overcome any significant outdoor weather changes causing ‘hourly’ fluctuations and this justifies the ‘daily’ fluctuations existing well below the safe thresholds.

7. Conclusions

This study presents the effects of renovation intervention on the indoor hygrothermal environment in a historical art gallery building of cultural significance. The study directly caters to the lack in existing literature on post-renovation assessment methods, to study the intervention impacts on the indoor hygrothermal conditions in a restricted environment. The assessment is based in the NGS, where a large scale refurbishment activity was carried out in August 2013, mainly to improve the indoor conditions towards good health of the housed collections.

A synthetic indicator, Renovation Impact Index (RII), was developed in this study to represent the intervention impacts in terms of quantified gradient of the performances of the two hygrothermal parameters critical for artwork conservation. The performance of these two parameters were defined in terms of synthetic indices, known as Performance Index (PI), as used in recent studies [5,7,18]. These indices represented the adherence of the indoor hygrothermal environment quality to the desired T and RH specifications set by the conservation requirements. These specifications provided a window, relative to which the PI was calculated. In this study two windows were considered to define the PI – ‘fixed’ window using BS5454 Standards, and ‘relaxed’ window based on recent studies and proposals.

The positive effects of the renovation solutions including the upgrade of skylight, building fabric insulation and balancing of the AHUs were evident. Supply air ducting reconfiguration and increased fan speeds ensured an improved and uniform supply air flow rates in the gallery rooms, and this greatly affected the indoor hygrothermal performance, as evident with a positive RII estimate of 15.56% RII for T and 3.93% RII for RH. It is, however, worth noting that even with the high RII, indoor T improved to a performance of only 26.65% PI which indicated that for the significant remaining cases, the T inside Gallery 11 existed beyond the BS5454 specifications.

The skylight upgrade ensured less fabric heat loss and combined with the building fabric insulation measures, the building now retains the heat provided by space heating and internal heat gains better, leading to less heating demand. This is reflected by the significantly reduced gas consumption (27%) on which the heating system relies.

Global PI was established as a correlation of T and RH to study the combined performance of the hygrothermal parameters with respect to the fixed BS5454 specified window and the adaptable seasonal set point window. Naturally, the hygrothermal performance experienced better PI estimates in the 'relaxed' adaptable set-points window; a higher RII estimate for the fixed BS5454 window highlighted that the impact is more pronounced owing to the greater room for improvement with respect to the tight BS5454 thresholds.

A seasonal influence on the renovation impact was studied by splitting the annual periods into –hot, mild and cold months. The most pronounced improvement is observed during winter with a Global RII of 59%. Separate seasonal study of T and RH performance revealed a significant case of overheating before the refurbishment. As the cold outdoor air gets heated and enters the room, the RH drops significantly. The improved building fabric insulation and double glazed skylight ensures lesser heating requirement, hence eliminating chances of overheating. RH performance improved significantly more than T, if looked through both the fixed BS5454 and adaptable windows. T is observably allowed to drift more loosely along the set-points in order to ensure an adequate RH performance, with RH being more critical to artwork conservation.

The indoor hygrothermal stability was assessed using daily and hourly fluctuation parameters defined in accordance to the NGS requirements and aligning with recent studies [7,18]. The RII figures demonstrated that the NGS experiences a very stable indoor hygrothermal quality with only hourly RH showing scope of improvement, which it did by 11% on the scale of Fluctuation RII. The skylight glazing and improved fabric insulation ensures the building is now less influenced by outdoor weather changes. The high thermal mass of the building further offsets all the 'hourly' fluctuations, if any, leading to very low 'daily' fluctuations existing well below the thresholds defined in Standards.

The proposed methods can be extended to other renovation projects in similar buildings for impact study and assist the building management to effectively and clearly visualise the improvement extent relative to their intervention measures and goals. With the RII effectively summarising the quantified improvements after the renovation works, the building management also has the option to go for a detailed study of the indoor environmental performance over a year and in each individual season.

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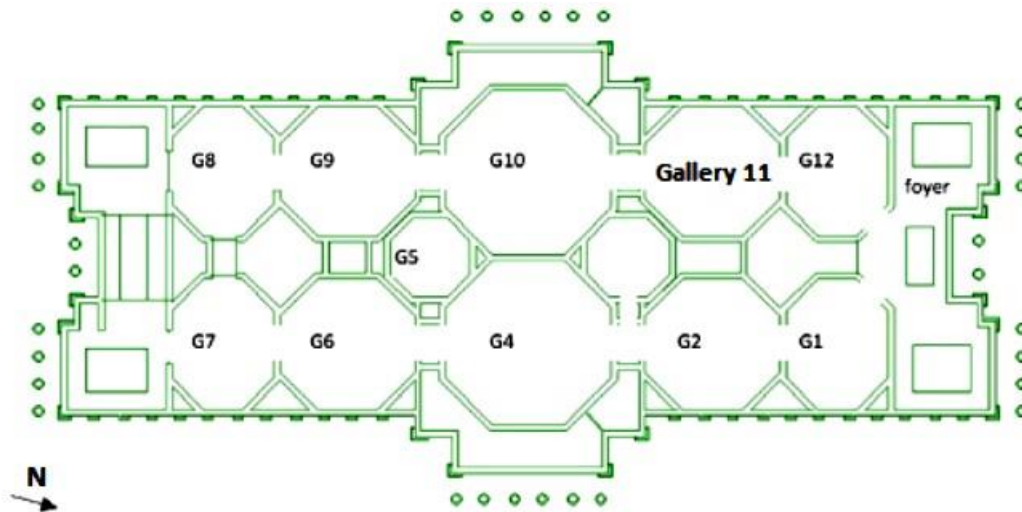


Figure 1 – The art gallery in a historical building considered for the study (top), Floor plan of the art gallery (bottom)



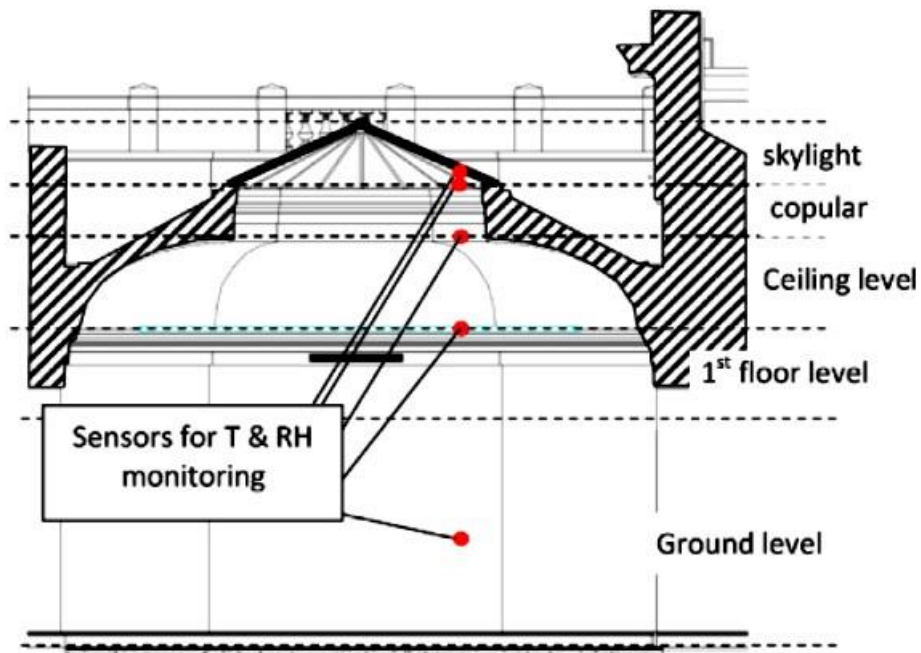


Figure 2 - Gallery 11 interior with colossal paintings (top), Gallery 11 cross-section with sensors for T/RH monitoring (bottom)

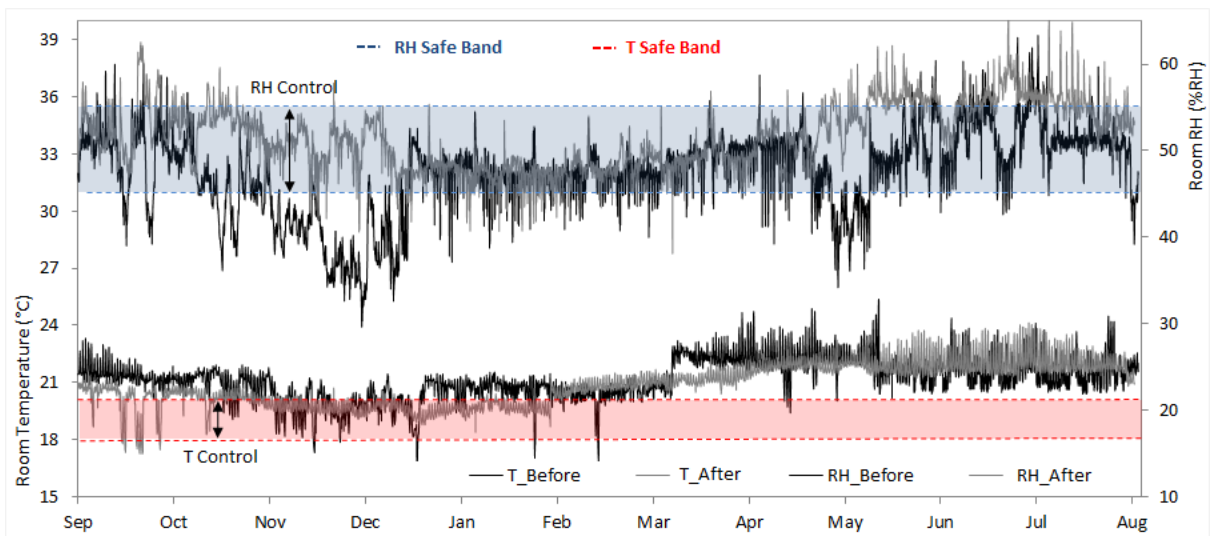


Figure 3 - Comparison of Annual Indoor Environmental Control Quality (Before and After Refurbishment)

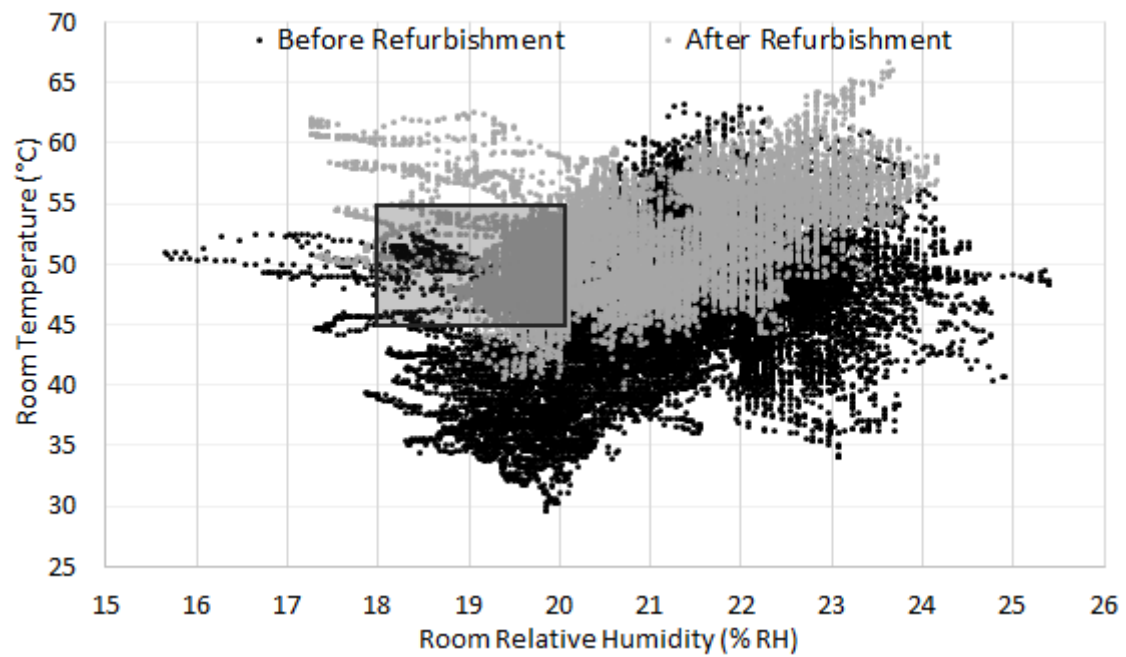
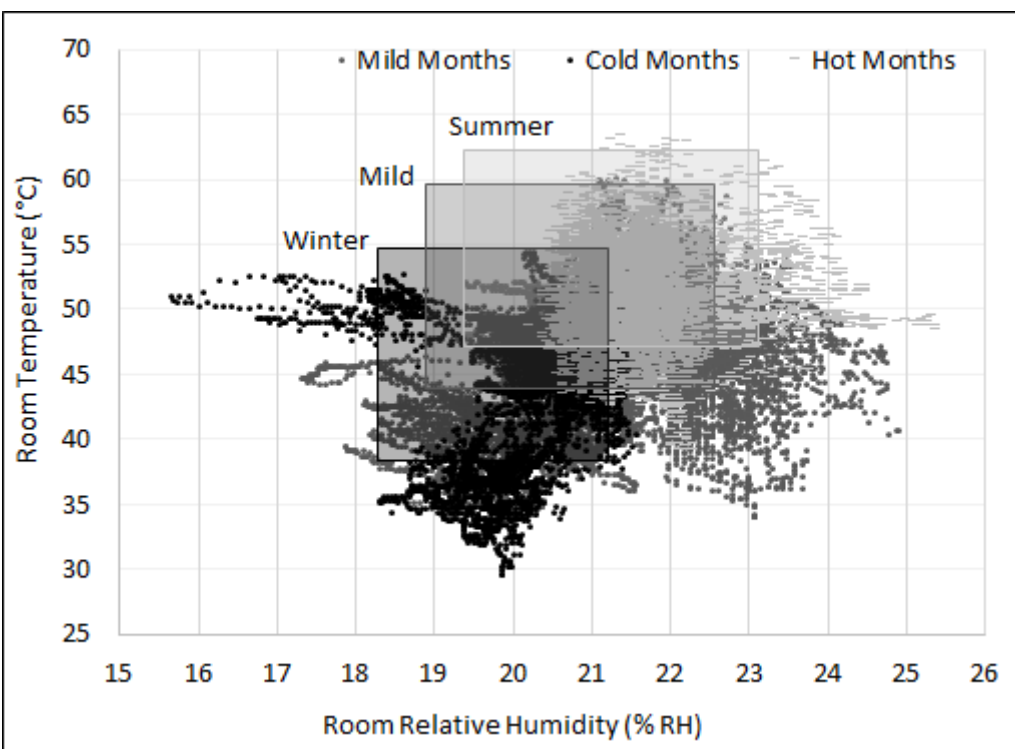


Figure 4 – Annual comparison of Global PI for T against RH, before and after the refurbishment (with Fixed Band Window)



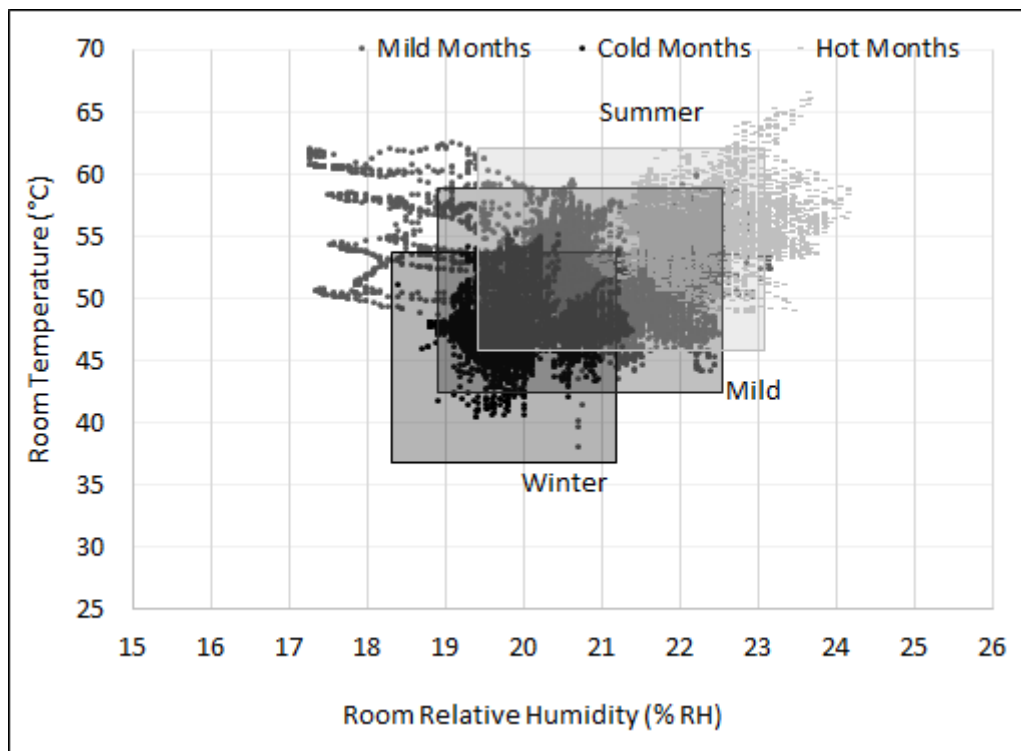


Figure 5 – Seasonal comparison of Global PI for T against RH, before (Top) and after (Bottom) refurbishment (with Adaptable Seasonal Windows)

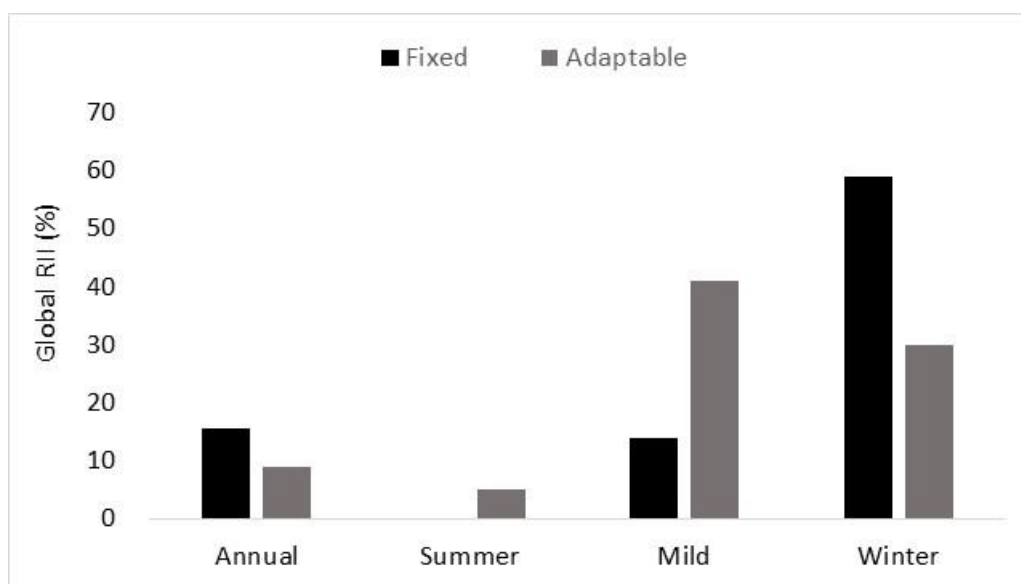


Figure 6– Global RII comparison for improvements in two spectra – Fixed BS5454 set-points and Adaptable Seasonal Set-points strategy

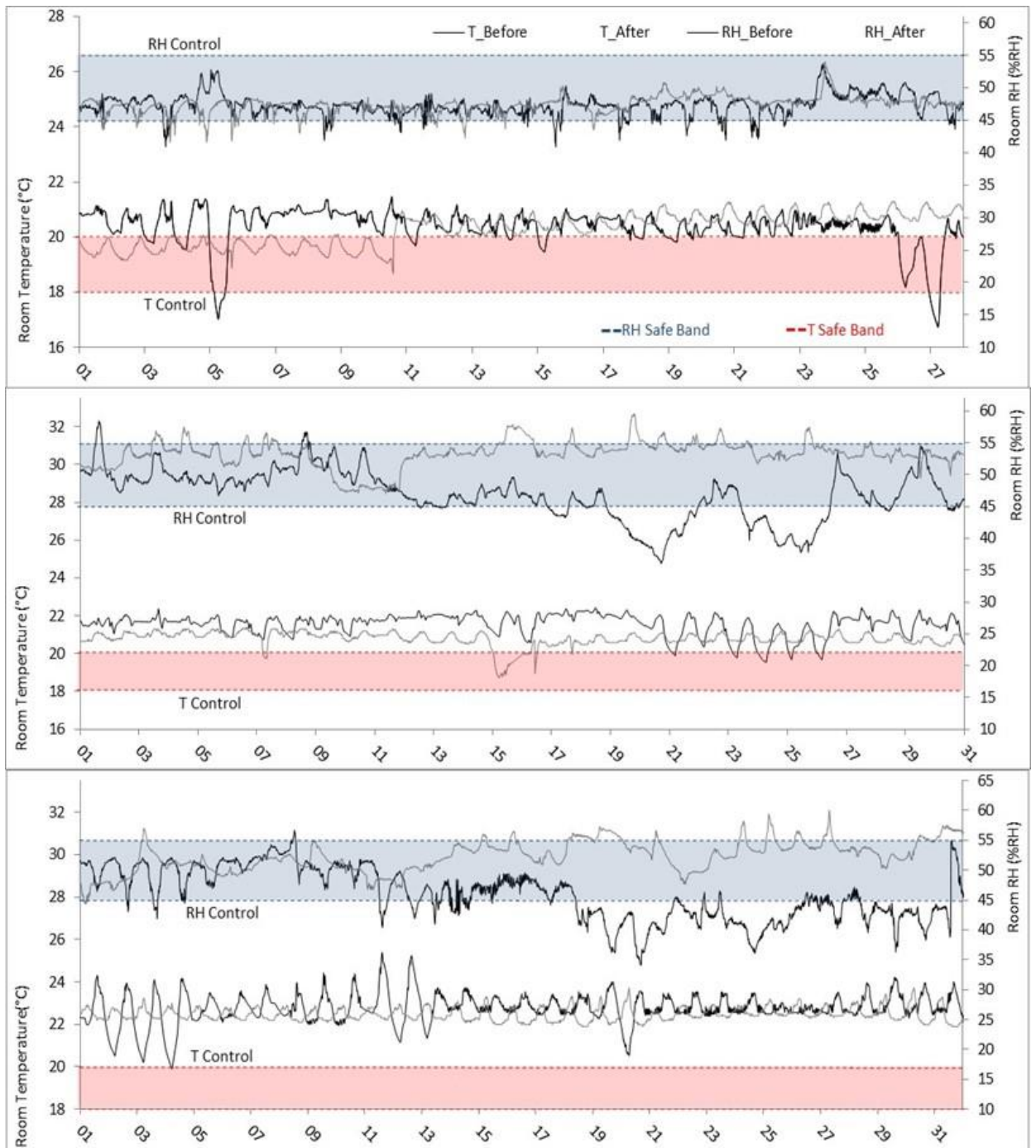


Figure 7 - Seasonal analysis - Indoor environment in a) Cold month b) Mild month c) Hot month

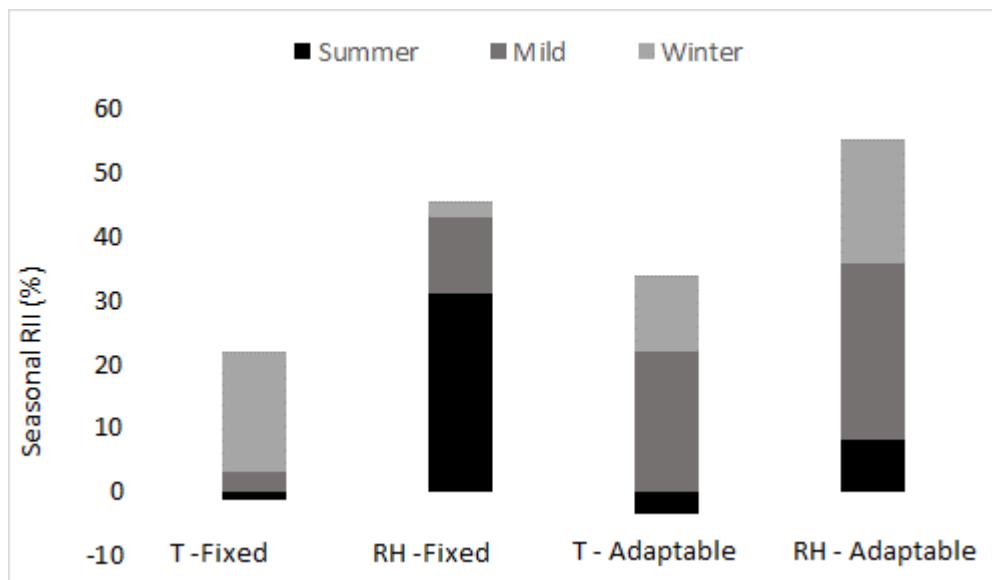
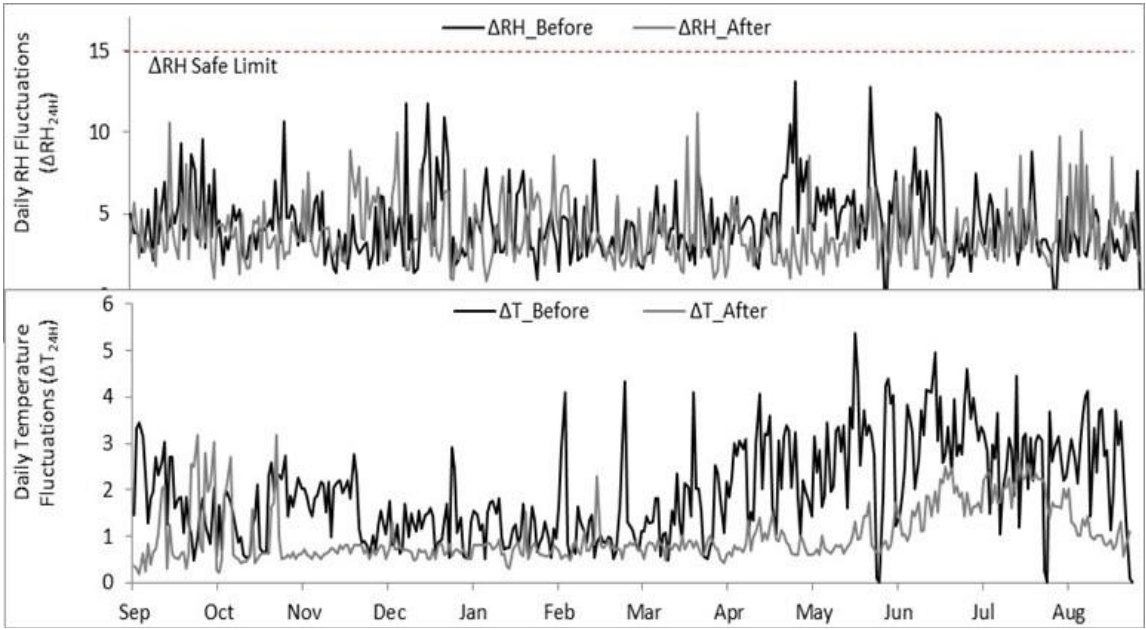


Figure 8 – Seasonal RII for indoor T and RH over two spectra – Fixed BS5454 set-points and Adaptable Seasonal Set-points strategy

462
463

a)



464
465

b)

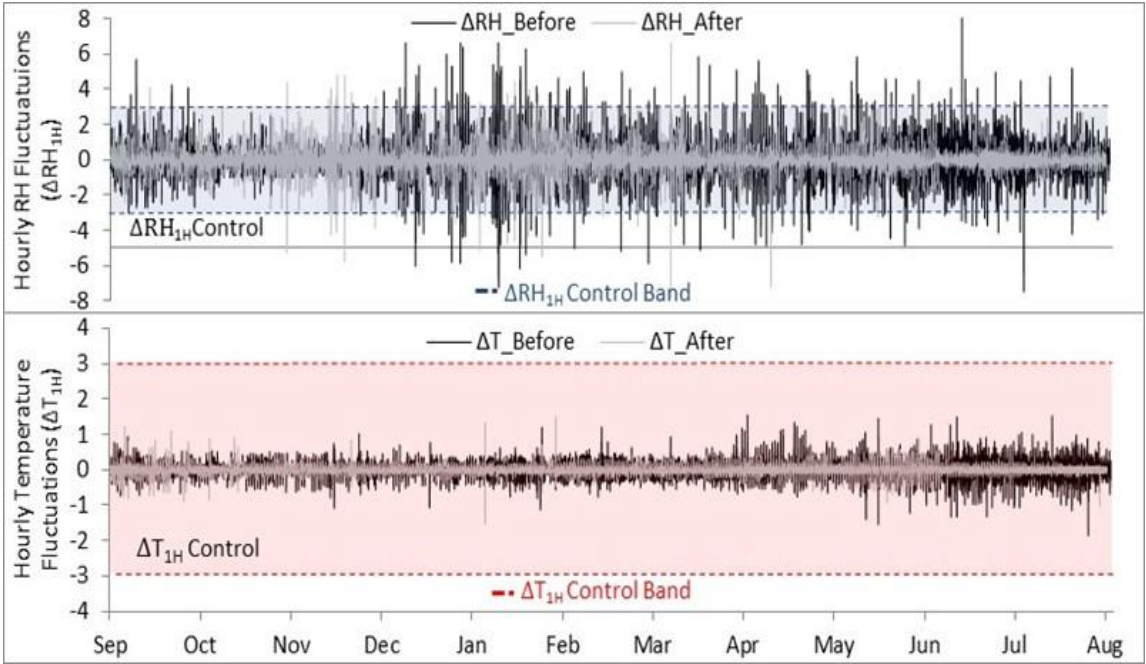


Figure 9 -Comparison of T and RH fluctuations before and after the refurbishment for a year –
a) daily fluctuations b) hourly fluctuations

LIST OF TABLES

Table 1

Standards for Collection Care followed at NGS

| Indoor Environmental Parameter | Specified Range |
|--------------------------------|-----------------|
| T (°C) | 18-20 |

| Temporal T /RH Gradients (°C)/(%RH) | RH (%RH) | 45-55 |
|-------------------------------------|----------|-------|
| | Hourly | ±3 |
| | Daily | ±15 |

Table 2

Refurbishment activity at the NGS

| | Pre-Refurbished State | Recommended Activity | Refurbished State |
|--------------------|--|---|---|
| Skylight Glazing | Single Glazed <i>U-Value:</i> 5.26 <i>Configuration:</i> 20mm Clear Glass | Upgrade to double glazing in order to reduce the building's fabric heat loss | Double Glazed <i>U-Value:</i> 2.25 <i>Configuration:</i> Outer layer – 6.0mm solar control Cavity layer – 16.0mm air gap Argon filled Inner layer – 8.0mm opal polycarbonate to min. 50% light transmission |
| Fabric Insulation | Gaps along the perimeter of skylights and cupola surface | Building fabric – review all roof lights with a view to improve draught proofing | Well insulated and draught proofed |
| AHU Balancing | <i>AHU 1:</i> Galleries 1-6, 9-12, A1 <i>AHU 2:</i> Galleries 7-8, A2-A5, photo store | Reconfigure supply ducting at roof level to enable gallery 6 and 9 to be served by AHU2 instead of AHU 1. | <i>AHU 1:</i> Galleries 1-4, 10-12, A1 <i>AHU 2:</i> Galleries 5-9, A2-A6, photo store |
| Increase Fan Speed | AHU 1 air change per hour: 0.9 – 2.1 ach (very low compared to BS 5454 design Standard of 4-6 ach) | Change the AHU 1 supply and extract motor pulleys to achieve approximately 15-20% increase in air flow rate | Installation complete. (Existing flow rates not assessed/available) |

Table 3

Tiny Tag Ultra2 Temperature/Humidity Loggers (TGU-4500)

| | |
|-------------------------|---|
| Measurement Range T/RH | -25° C to +85° C / 0% to 95% RH |
| Sensor Type T/RH | 10K NTC Thermistor / Capacitive |
| Accuracy T/RH | +0.4% (from 0° to 40° C) / ±3.0%RH at 25° C |
| Response Time T/RH | 20 mins to 90% FSD / 10 seconds to 90% FSD |
| Reading Resolution T/RH | 0.01° C or better / Better than 0.3% RH |
| Logging Interval | 1 second to 10 days |

Table 4

Seasonal safe band specifications for the hygrothermal variables (Harley Haddow)

| Season | Period | T (°C) | RH (%) |
|--------|----------------------|---------|---------|
| Winter | Dec – Feb | 18 – 21 | 41 – 55 |
| Mild | Mar – May, Sep – Nov | 19 – 22 | 45 – 60 |
| Summer | Jun – Aug | 20 – 23 | 47 – 63 |

Table 5

RII for annual temporal profile of indoor T/RH

| | Electricity (kWh/m ²) | Gas (kWh/m ²) | T (%PI) | RH (%PI) |
|--------|-----------------------------------|---------------------------|---------|----------|
| Before | 245 | 300 | 11.09 | 73.54 |
| After | 200 | 220 | 26.65 | 77.47 |
| RII | | | 15.56 | 3.93 |

Table 6

Global RRI (T vs RH) for annual period and individual seasonal hygrothermal performances

| PI (%) | Annual | | Summer | | Mild | | Winter | |
|--------|---------|---------|---------|---------|---------|---------|---------|---------|
| | BS 5454 | Relaxed | BS 5454 | Relaxed | BS 5454 | Relaxed | BS 5454 | Relaxed |
| Before | 11.09 | 88 | 0 | 85 | 1.5 | 48 | 10 | 67 |
| After | 26.65 | 97 | 0 | 90 | 15.5 | 89 | 69 | 97 |
| RII | 15.56 | 9 | 0 | 5 | 14 | 41 | 59 | 30 |

Table 7

Seasonal influence on RII in two spectra –

a) Fixed BS5454 standards

| PI (%) | T _{Summer} | RH _{Summer} | T _{Mild} | RH _{Mild} | T _{Winter} | RH _{Winter} |
|--------|---------------------|----------------------|-------------------|--------------------|---------------------|----------------------|
| Before | 1.1 | 55.67 | 7.92 | 73.75 | 13.16 | 93.56 |
| After | 0 | 86.6 | 10.92 | 85.78 | 32 | 96 |
| RII | -1.1 | 30.93 | 3 | 12.03 | 18.84 | 2.44 |

b) Adaptive Seasonal bands

| PI (%) | T _{Summer} | RH _{Summer} | T _{Mild} | RH _{Mild} | T _{Winter} | RH _{Winter} |
|--------|---------------------|----------------------|-------------------|--------------------|---------------------|----------------------|
| Before | 93.34 | 90.84 | 67.52 | 70.83 | 85.71 | 80.35 |
| After | 90 | 98.92 | 89.54 | 98.61 | 97.44 | 99.88 |
| RII | -3.34 | 8.08 | 22.02 | 27.78 | 11.73 | 19.53 |

Table 8

RII for indoor hygrothermal stability – hourly and daily fluctuations

| PI (%) | ΔT_{1H} | ΔRH_{1H} | ΔT_{24H} | ΔRH_{24H} |
|--------|-----------------|------------------|------------------|-------------------|
| Before | 100 | 88.14 | 100 | 100 |
| After | 100 | 99.42 | 100 | 100 |
| RII | NA | 11.28 | NA | NA |